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14. ABSTRACT

The objectives of project are: (1) inducing chaos in electronic circuits, and (2) anti-jamming with stochastic resonance. In close collaboration with AFRL scientists, we developed a general scheme to experimentally induce robust chaotic attractors in electronic circuits (Objective 1). For Objective 2, we discovered a measure to characterize stochastic resonance that has much higher sensitivity to noise variations than all existing measures. We expect it to be useful in various applications. In addition, we obtained interesting results on a number of related topics in nonlinear dynamics. The outcomes of the project are 36 papers published in, accepted by, or submitted to refereed journals (including 5 papers published in *Physical Review Letters*). During the project period, 3 Ph.D and 7 Master students graduated under the supervision of the PI, and over 30 invited talks were given by the PI all over the world on the proposed research and related topics.

15. SUBJECT TERMS
Nonlinear Dynamics, Inducing Chaos, Electronics Circuits, Stochastic Resonance

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Final Report

This report summarizes activities under the Air Force Office of Scientific Research (AFOSR) Grant No. F49620-03-1-1290 entitled "Research on Nonlinear Dynamics with Defense Applications." The duration of the project is 5/1/2003 to 4/30/2006. The report is divided into the following Sections:

1. Objectives
2. Description of Achievements of Objectives
3. Related Accomplishments and New Findings
4. Personnel Supported and Theses Supervised by PI
5. List of Publications
6. Interactions/Transitions
7. Past Honors

1 Objectives

1. Inducing chaos in electronic circuits;
2. Antijamming using stochastic resonance.

2 Description of Achievements of Objectives

Both Objectives have been accomplished. Results have been published in a number of refereed-journal papers.

2.1 Inducing chaos in electronic circuits

In defense applications it may be desirable to induce chaos in nonlinear oscillators operating in a stable regime. Examples of such oscillators are circuits embedded in electronic tracking and guidance systems. Chaos may confuse these systems so that it is more likely for them to fail in their intended mission. Inducing chaos to interrupt the normal operation of the circuit can be regarded as advantageous because the absorbed energy required may be much less than that needed to simply "overpower" the same electronics by using large-amplitude excitations. Previous methods on inducing or maintaining chaos in nonlinear dynamical systems assume that either the system is in a transiently chaotic regime, or a parameter or state variable of the system is directly accessible for adjustment, or the system equations are available. For our problem of disturbing a target electronic circuit, none of these conditions can be met.

In close collaboration with AFRL scientists (Drs. John Gaudet and Mike Harrison), we have developed a general scheme to induce chaotic attractors in electronic circuits. The applications of interest, e.g., defeating electronic tracking and guidance systems, stipulate the following three constraints: (1) the circuit operates in a stable periodic regime far away from chaotic behavior, (2) no parameters or state variables of the circuit are directly accessible to adjustment, and (3) the circuit equations are unknown. Under these conditions, a viable approach to inducing chaos is to use external excitations such as a microwave signal, assuming that a proper coupling mechanism exists and allows the circuit to be perturbed by the excitation. We have addressed the basic question of how to choose the waveform of the excitation to ensure that chaotic attractor can be generated in the circuit. In particular, we have demonstrated that weak resonant perturbations with time-varying frequency and phase are generally able to drive the circuit into a hierarchy of nonlinear resonant states and eventually into chaos. In addition to theoretical analysis and numerical verifications, we have experimentally realized the scheme by using a Duffing-type of nonlinear electronic oscillator (originally developed by C. Silva and A. Young from the Aerospace Corporation), driven by a phase-locked loop circuit. The phase-locked loop can track the frequency and phase evolutions of the target Duffing circuit and deliver resonant perturbations to generate robust chaotic attractors.

A brief account of the work has been published in *Physical Review Letters.* An extensive and detailed manuscript has been submitted to *IEEE Transactions on Circuits and Systems I.* (Dr. John Gaudet is a co-author on both manuscripts.)

Future efforts will focus on defense applications and further theoretical, numerical, and experimental explorations. For instance, a requirement in our present method is that a real-time signal from the target circuit be available so that the resonant frequency and phase can be calculated. In applications, this "monitoring" requirement may not be met. It is thus necessary to address the issue of inducing chaos in a "generic" circuit that is the core in any electronic tracking and guidance system, without the requirement of system monitoring. Such a generic circuit can be MOSFET based microelectronic circuits that are widely used in all types of electronic devices. We will develop theoretical understanding

of the existing experimental work on the effects of microwave excitations on microelectronic circuit components. Considering that the present method is capable of inducing only low-dimensional chaos, an interesting question is how to induce high-dimensional chaos that would potentially have higher destructive power. We will develop theory, numerical, and experimental tests on electronic circuits to address this question.

Most relevant publications

- Y.-C. Lai, A. Kandangath, S. Krishnamoorthy, J. A. Gaudet, and A. P. S. de Moura, "Inducing chaos by resonant perturbations: theory and experiment," Physical Review Letters 94, 214101(1-4) (June 2005).

- A. Kandangath, S. Krishnamoorthy, Y.-C. Lai, and J. A. Gaudet, "Inducing chaos in electronic circuits by resonant perturbations," submitted to *IEEE Transactions on Circuits and Systems I.*

2.2 Antijamming using stochastic resonance

Our efforts in this area are motivated by the problem of antijamming. In applications it is necessary to carry out signal processing in noisy and jamming environment. The possible beneficial role of noise through the mechanism of stochastic resonance (SR) suggests a non-conventional approach to antijamming: using noise to counter noise. To implement this strategy in realistic applications, it is necessary to determine the optimal noise level. A fundamental issue thus concerns a proper measure that exhibits a high sensitivity to noise. The difficulty with existing measures for the characterization of SR is that they vary slowly with noise about the optimal value, exhibiting a "bell-shape" behavior. These measures are therefore not suitable for the applications of our interest.

We have worked out a measure of SR that has an extremely high sensitivity to noise. More precisely, the measure as a function of the noise amplitude exhibits a cusp-like behavior about the optimal noise level. Our success is built upon the recent idea that SR can be understood as a manifestation of phase synchronization (PS) between the input and the output signals. A brief account of the main result has been published in *Europhysics Letters.* An extensive and detailed version of the work has recently been accepted by *Mathematical Biosciences and Engineering.*

As a byproduct, we have discovered, through analysis and computation of a class of population models, that noise can promote species diversity in nature through the mechanism of SR. One paper emphasizing the role of the SR aspect has been published in *Physical Review Letters.* Another paper presenting a detailed physical analysis of the scaling laws has been published in *Physical Review E.*

Future work will focus on (1) developing an analytic theory for the cusp-like behavior by using a two-state stochastic-resonance system and conducting experimental verification using microelectronic circuits, (2) investigation of whether the cusp-like behavior can occur with respect to frequency variations in noisy and/or jamming environment, and (3) exploration of the possibility of using SR for system/feature identification with applications in defense missions and in homeland security.

Most relevant publications

- K. Park, Y.-C. Lai, Z. Liu, and A. Nachman, "Aperiodic stochastic resonance and phase synchronization," *Physics Letters A* **326**, 391-396 (2004).

- Y.-C. Lai, Z. Liu, A. Nachman, and L. Zhu, "Suppression of jamming in excitable systems by aperiodic stochastic resonance," *International Journal of Bifurcation and Chaos* **14**, 3519-3539 (2004).

- K. Park and Y.-C. Lai, "Characterization of stochastic resonance," *Europhysics Letters* **70**, 432-438 (2005).

- Y.-C. Lai and Y. Liu, "Noise promotes species diversity in nature," *Physical Review Letters* **94**, 038102 (2005).

- Y.-C. Lai, "Beneficial role of noise in promoting species diversity through stochastic resonance," *Physical Review E* **72**, 042901 (2005).
  This work was selected by the Virtual Journal of Biological Physics Research for the November 1, 2005 issue (http://www.vjbio.org).

- Y.-C. Lai and K. Park, "Noise sensitive measure for characterization of stochastic resonance in biological oscillators," *Mathematical Biosciences and Engineering*, accepted.

- K. Park, S. Krishnamoorthy, Y.-C. Lai, and A. Kandangath, "Noise-induced phase synchronization: nonmonotonicity and stochastic resonance," submitted to *Chaos*.

- K. Park, Y.-C. Lai, and S. Krishnamoorthy, "Noise sensitivity of phase-synchronization time in stochastic resonance: theory and experiment," submitted to *Physical Review E*.

3 Related Accomplishments and New Findings

Besides the accomplishments of the main Objectives, we have also obtained a number of interesting results in the general field of nonlinear science, which are motivated by or related to the Objectives of the project. A brief description of some of the results is given below.

3.1 Limits to chaotic phase synchronization

Phase synchronization in coupled chaotic oscillators, situation where the phase differences of the oscillators are bounded while their amplitudes remain uncorrelated, can occur for chaotic attractors corresponding to proper rotations in the phase space. As applications of phase synchronization become widespread, it is important to understand its limits. We have discovered that phase synchronization in the above sense cannot occur for the general class of coupled Lorenz-type of chaotic oscillators. For such a system, intermittent synchronization between the dynamical variables sets in as soon as an originally null Lyapunov exponent becomes negative.

- L. Zhao, Y.-C. Lai, R. Wang, and J.-Y. Gao, "Limits to chaotic phase synchronization," *Europhysics Letters* **66**, 324-330 (2004).

3.2 Aperiodic stochastic resonance and phase synchronization

Aperiodic stochastic resonance and phase synchronization were considered to be different phenomena in nonlinear physics which had been discovered at about the same time. The former means enhancement of aperiodic signals by noise, while the latter characterizes a phase coherence in weakly coupled nonlinear oscillators. We have demonstrated that aperiodic stochastic resonance can be related to phase synchronization between the input and output signals. We have introduced a measure to characterize the degree of phase synchronization and showed its equivalence to a commonly used measure to quantify aperiodic stochastic resonance.

- K. Park, Y.-C. Lai, Z. Liu, and A. Nachman, "Aperiodic stochastic resonance and phase synchronization," *Physics Letters A* **326**, 391-396 (2004).

3.3 Stability of attractors formed by inertial particles in open chaotic flows

Particles having finite inertia and size advected in open chaotic flows can form attractors behind structures. Depending on the system parameters, the attractors can be chaotic or nonchaotic. But how robust are these attractors? In particular, will small, random perturbations destroy the attractors? We have addressed this question by utilizing a prototype flow system: a cylinder in a two-dimensional imcompressible flow, behind which von Karman vortex street forms. Our finding is that attractors formed by inertial particles behind the cylinder are fragile in that they can be destroyed by small noise. However, the resulting chaotic transient can be superpersistent in the sense that its lifetime obeys an exponential-like scaling law with the noise amplitude, where the exponent in the exponential dependence can be large for small noise. This happens regardless of the nature of the original attractor, chaotic or nonchaotic. We have obtained numerical evidence and derived a theory to explain this phenomenon. Our finding may make direct experimental observation of superpersistent chaotic transients feasible and it may also have implications to problems of current concern such as the transport and trapping of chemically or biologically active particles in large scale, environmental flows.

- Y. Do and Y.-C. Lai, "Superpersistent chaotic transients in physical space - advective dynamics of inertial particles in open chaotic flows under noise," *Physical Review Letters* **91**, 224101(1-4) (2003).

- Y. Do and Y.-C. Lai, "Stability of attractors formed by inertial particles in open chaotic flows," *Physical Review E* **70**, 036203(1-10) (2004).

3.4 Scaling laws for noise-induced superpersistent chaotic transients

A superpersistent chaotic transient is characterized by the following scaling law for its average lifetime: $\tau \sim \exp[C(p-p_c)^{-\alpha}]$, where $C > 0$ and $\alpha > 0$ are constants, $p \geq p_c$ is a bifurcation parameter, and p_c is its critical value. As p approaches p_c from above, the exponent in the exponential dependence diverges, leading to an extremely long transient lifetime. Historically the possibility of such transient raised the question of whether asymptotic attractors are relevant to turbulence. We have investigated the phenomenon of noise-induced superpersistent chaotic transients by constructing a prototype model based on random maps. The model can be analytically solved by stochastic differential equations, leading to several scaling laws for the transient lifetime versus the noise amplitude ε for both the subcritical ($p < p_c$) and the supercritical ($p > p_c$) cases. We find that, in the subcritical case where a chaotic attractor exists in the absence of noise, noise-induced transients can be more persistent in the following sense of double-exponential and algebraic scaling: $\tau \sim \exp[K_0 \exp(K_1 \varepsilon^{-\gamma})]$ for small noise amplitude ε, where $K_0 > 0$, $K_1 > 0$, and $\gamma > 0$ are constants. The longevity of the transient lifetime in this case is striking. For the supercritical case where there is already a superpersistent chaotic transient, noise can significantly reduce the transient lifetime, in contrast to a previous belief. These results add to the understanding of the interplay between random and deterministic chaotic dynamics with surprising physical implications.

- Y. Do and Y.-C. Lai, "Extraordinarily superpersistent chaotic transients," *Europhysics Letters* **67**, 914-920 (2004).

- Y. Do and Y.-C. Lai, "Scaling laws for noise-induced superpersistent chaotic transients," *Physical Review E* **71**, 046208(1-11) (2005).

3.5 A Trick to Remember: Capacity of oscillatory associative-memory networks with error-free retrieval

Networks of coupled periodic oscillators (similar to the Kuramoto model) have been proposed as models of associative memory. However, error-free retrieval states of such oscillatory networks are typically unstable, resulting in near-zero capacities. This puts the networks at disadvantage as compared with the classical Hopfield network. We have proposed a simple remedy for this undesirable property and showed rigorously that the error-free capacity of our oscillatory, associative-memory networks can be made as high as that of the Hopfield network. They can thus not only provide insights into the origin of biological memory, but can also be potentially useful for applications in information science and engineering.

This research has been featured in a number of public media including Physical Review Focus (March 12, 2004), Invovations Report, KurzweilAI.net, and ASU Insight.

- T. Nishikawa, Y.-C. Lai, and F. C. Hoppensteadt, "Capacity of oscillatory associative-memory networks with error-free retrieval," *Physical Review Letters* **92**, 108101(1-4) (2004).

- T. Nishikawa, F. C. Hoppensteadt, and Y.-C. Lai, "Oscillatory associative memory network with perfect retrieval," *Physica D* **197**, 134-148 (2004).

3.6 Strange nonchaotic attractors in random dynamical systems

Whether strange nonchaotic attractors (SNAs) can occur typically in dynamical systems other than quasiperiodically driven systems has been an open question for long. We have discovered, based on a physical analysis and numerical evidence, that robust SNAs can be induced by small noise in autonomous discrete-time maps and in periodically driven continuous-time systems. These attractors, which are relevant to physical and biological applications, can thus be expected to occur more commonly in dynamical systems than previously thought.

- X.-G. Wang, M. Zhan, C.-H. Lai, and Y.-C. Lai, "Strange nonchaotic attractors in random dynamical systems," *Physical Review Letters* **92**, 074102(1-4) (2004).

- X.-G. Wang, Y.-C. Lai, and C. H. Lai, "Characterization of noise-induced strange nonchaotic attractors," submitted to *Physical Review E.*

3.7 Beneficial role of noise in promoting species diversity through stochastic resonance

Understanding the factors generating and maintaining the species diversity in nature is one of the central goals in ecological sciences. There is an increasing recognition that patterns in species diversity cannot be understood without reference to nonequilibrial dynamics. As diversity is accomplished by coexistence, it is important to identify and study factors that control species coexistence. Previous works suggested the role of unstable dynamics (e.g., chaos) in promoting coexistence. We have investigated the role in species coexistence played by inevitable random fluctuations in the environment. In particular, we have utilized a prototype model where, in a spatialtemporal environment, inferior but rapidly moving species can coexist with superior but relatively stationary species. The model consists of two interacting species in a two-patch environment. We have demonstrated that chaotic dynamics can provide the spatiotemporal variation in the fitness required for coexistence, via the dynamical mechanism of synchronization and intermittency. Incorporating noise in an ecologically meaningful manner, we have discovered an SR phenomenon through which noise can significantly enhance the degree of coexistence and thereby promote species diversity.

- Y.-C. Lai and Y. Liu, "Noise promotes species diversity in nature," *Physical Review Letters* **94**, 038102 (2005).

- Y.-C. Lai, "Beneficial role of noise in promoting species diversity through stochastic resonance," *Physical Review E* **72**, 042901 (2005).

3.8 Unstable periodic orbits and transition to intermittent chaotic synchronization

Coupled chaotic oscillators occur in a large variety of physical, chemical, and biological systems. They can exhibit intermittent synchronization in the weakly coupling regime, as characterized by the entrainment of their dynamical variables in random time intervals of finite duration. We have found that the transition to intermittent synchronization can be characteristically distinct for geometrically different chaotic attractors. In particular, for coupled phase-coherent chaotic attractors such as those from the Rössler system, the transition occurs immediately as the coupling is increased from zero. For phase-incoherent chaotic attractors as those in the Lorenz system, the transition occurs only when the coupling is sufficiently strong. We developed a theory based on the behavior of the Lyapunov exponents and unstable periodic orbits to understand these distinct transitions.

- L. Zhao, Y.-C. Lai, and C.-W. Shih, "Transition to intermittent chaotic synchronization," *Physical Review E* **72**, 036212(1-7) (2005).

3.9 Noise-induced phase synchronization: nonmonotonicity and stochastic resonance

The problem of noise-induced synchronization has been a subject of interest in statistical and nonlinear physics. We have discovered a surprising phenomenon: the average synchronization time exhibits a universal, nonmonotonic behavior with the noise amplitude. In particular, in the presence of deterministic coupling, the average phase-synchronization time exhibits a local minimum for relatively small noise amplitude and a local maximum for stronger noise. We have provided a physical theory, numerical computations, and laboratory experiments using electronic circuits to establish the phenomenon.

- K. Park, S. Krishnamoorthy, Y.-C. Lai, and A. Kandangath, "Noise-induced phase synchronization: nonmonotonicity and stochastic resonance," submitted to *Chaos*.

3.10 Basins of attraction in piecewise smooth Hamiltonian systems

Piecewise smooth Hamiltonian systems arise in physical and engineering applications. For such a system typically an infinite number of quasiperiodic "attractors" coexist. [Here we use the term "attractors" to indicate invariant sets to which typically initial conditions approach, as a result of the piecewise smoothness of the underlying system. These "attractors" are therefore characteristically different from the attractors in dissipative dynamical systems.] We found that the basins of attraction of different "attractors" exhibit a riddled-like feature in that they mix with each other on arbitrarily small scales. This practically prevents prediction of "attractors" from specific initial conditions and parameters. The mechanism leading to the complicated basin structure has been found to be distinct from those reported previously for similar basin structures in smooth dynamical systems. The phenomenon has been demonstrated in a class of electronic relaxation oscillaltors with voltage protection.

- Y.-C. Lai, D.-R. He, and Y.-M. Jiang, "Basins of attraction in piecewise smooth Hamiltonian systems," *Physical Review E (Rapid Communications)* **72**, 025201 (2005).

3.11 Noise-induced intermittency in nonlinear waves

The investigation of the effect of noise on dynamical systems has led to the discoveries of a number of remarkable phenomena in nonlinear physics. Examples include stochastic resonance, noise-induced synchronization, and noise-triggered crises and intermittency. Most previous works on intermittency have explored relatively low-dimensional dynamical systems, such as those described by maps or flows in a few phase-space dimensions. There are many physical phenomena, such as nonlinear waves, for which a description based on low-dimensional maps or flows is inadequate. Instead, they are usually modeled by nonlinear partial differential equations (PDEs), which are in principle infinitely dimensional dynamical systems. Whether and how noise can induce intermittency, and its physical significance, are of great interest. By utilizing a class of systems modeling a number of wave phenomena in fluids and plasmas, we have found that noise can induce intermittent energy bursts. The time intervals between successive bursts are found to obey an exponential distribution. A spectral-coefficient based phase space is constructed to understand the dynamics responsible for the intermittency.

- L. Rajagopalan, Y.-C. Lai, K. Park, and G. Hu, "Noise-induced intermittent energy bursts in nonlinear waves," submitted to *Physical Review Letters.*

3.12 Effect of frequency mismatch of resonant perturbations on attractors

We have learned from freshman physics that for a linear oscillator, resonant forcing with frequency matching the internal frequency of the oscillator can generate oscillations of arbitrarily large amplitude. For a nonlinear oscillator, researchers have discovered that resonant perturbations can cause characteristic changes in the system's asymptotic behavior. For instance, for control of chaos, resonant forcing of small amplitude can convert a chaotic attractor into periodic, and vice versa. But what is the effect of frequency mismatch on the attractors of the nonlinear oscillator under resonant perturbation? By addressing this question, we find a class of attractors that are not chaotic but they exhibit a fractal geometry on finite scales. In particular, for such an attractor although its information dimension defined in the mathematical limit of infinitesimal scales is an integer, in finite scales the dimension assumes a fractional value. Physically, this is relevant because extremely small scales are not accessible due to noise. In order to understand the dynamical origin of the pseudo-strange attractors, we propose to interpret the effect of frequency mismatch as that due to a time-dependent parameter, so the resonantly forced system is effectively a nonstationary dynamical system where the parameter sweeps adiabatically through both periodic and chaotic regimes. Analysis based on the Melnikov function has provided insights into the transition to pseudo-strange attractors. As nonstationary dynamical systems with adiabatic parameter variations are useful models for a variety of physical and biological situations, we expect pseudo-strange attractors to be common.

- X.-G. Wang, Y.-C. Lai, and C. H. Lai, "Effect of resonant frequency mismatch on attractors," submitted to *Chaos.*

3.13 Effect of noise on generalized chaotic synchronization

When two characteristically different chaotic oscillators are coupled, generalized synchronization can occur. Motivated by the phenomena that common noise can induce and enhance complete synchronization or phase synchronization in chaotic systems, we have investigated the effect of noise on generalized chaotic synchronization by developing a phase-space analysis. The main prediction is that the effect can be system dependent in that common noise can either induce/enhance or destroy generalized synchronization. A prototype model consisting of a Lorenz oscillator coupled with a dynamo system has been used to illustrate these phenomena.

- S.-G. Guan, Y.-C. Lai, C. H. Lai, and X.-F. Gong, "Understanding synchronization induced by common noise," *Physics Letters A* **353**, 30-33 (2006).

- S.-G. Guan, Y.-C. Lai, and C. H. Lai, "Effect of noise on generalized chaotic synchronization," *Physical Review E*, accepted.

3.14 Extreme fluctuations of finite-time Lyapunov exponents in chaotic systems

In the study of nonlinear dynamical systems it is often desirable to know the Lyapunov exponents of the underlying dynamical invariant set. The exponents quantify the degree of system's sensitive dependence on initial conditions (the hallmark of chaos) and they are related to the fractal dimension of the invariant set. In computations large fluctuations of the finite-time exponents are of concern, as they can lead to incorrect estimates of the actual exponents. We have discovered that the extreme fluctuations of the finite-time exponents follow a general exponential distribution. This property holds both for deterministic systems and for physical systems where noise is present, in fairly typical situations such as crisis and noise-induced chaos. The result may be particularly relevant to experimental research of nonlinear physical systems or to nonlinear time-series analysis where Lyapunov exponents can be estimated only in relatively short time.

- Y.-C. Lai, "Extreme fluctuations of finite-time Lyapunov exponents in chaotic systems," submitted to *Chaos*.

3.15 Desynchronization waves in complex networks

A regular array of oscillators with random coupling exhibits transition from synchronized motion to desynchronized but ordered waves as a global coupling parameter is increased, due to the spread of localized instabilities of eigenvectors of the Laplacian matrix. We have recently found that shortcuts, which make the network small-world, typically destroy the ordered desynchronization wave pattern. A general type of the partial differential equation has been proposed to explain this interesting phenomenon. The results suggest that it is relatively more difficult to observe ordered wave patterns in complex networks.

- K. Park, L. Huang, and Y.-C. Lai, "Desynchronization waves in complex networks," submitted to *Physical Review Letters*.

4 Personnel Supported and Theses Supervised by PI

4.1 Personnel Supported

The following people received salaries from the AFOSR Project in various time periods.

- **Faculty (partial summer salary):**
  Ying-Cheng Lai (PI), Professor of Electrical Engineering, Affiliated Professor of Physics

- **Post-Doctoral Fellows (full-time or part-time appointments)**

1. Zong-Hua Liu (5/1/03-7/10/03)
2. Liang Zhao (9/1/03-2/29/04)
3. Liqiang Zhu (9/1/04-3/31/05)

4. Kwangho Park (10/1/03-4/30/06)

- **Graduate Students (part-time appointments)**

1. Younghae Do, Ph.D. student in Mathematics
2. Bin Xu, Master student in Electrical Engineering
3. Anil Kandangath, Master student in Electrical Engineering
4. Satish Krishnamoorthy, Master student in Electrical Engineering
5. Lakshmi Rajagopalan, Master student in Electrical Engineering
6. Edwin B. Ramayya, Master student in Electrical Engineering
7. Mayur Shah, Master student in Electrical Engineering
8. Suprada Urval, Master student in Electrical Engineering
9. Prasanna Surakanti, Master student in Electrical Engineering
10. Srinivasan Gopal, Master student in Electrical Engineering
11. Aditya Rao, Master student in Electrical Engineering

- **Visitors supported by the project**

1. Takashi Nishikawa, Visiting Assistant Professor, 5/16/04-8/15/04.
2. Tamás Tél, Visiting Professor (from Hungary), 8/26/04-9/10/04.
3. Jesus Seoane, Visiting Ph.D. student (from Spain), 9/15/04-12/15/04.
4. Gang Hu, Visiting Professor (from Beijing, China), 5/6/05-5/20/05.

4.2 Theses supervised by PI

- **Ph.D. Theses**

1. Younghae Do, Mathematics, ASU, May 2004. Dissertation: *Shadowing and noise-induced transient chaos.*
2. Liqiang Zhu, Electrical Engineering, ASU, August 2004. Dissertation: *Neural learning with applications to brain-machine interface.*
3. Antonio Rinaldi, Mechanical Engineering, ASU, December 2004. Dissertation: *Bridging the scales with statistical damage mechanics* (Joint supervision with Prof. Dusan Krajcinovic from ASU Department of Mechanical and Aerospace Engineering).

- **Master Theses**

1. Yirong Liu, Mathematics, May 2004. Thesis: *Noise promotes species diversity in nature.*
2. Mayur Shah, Electrical Engineering, August 2004. Thesis: *Integer ambiguity resolution with GPS signals in jamming environment.*

3. Anil K. Kandangath, Electrical Engineering, December 2004. Thesis: *Inducing chaos in electronic circuits by resonant perturbations.*

4. Suprada Urval, Electrical Engineering, May 2005. Thesis: *Antijamming of GPS signals.*

5. Sabrabh Gupta, Electrical Engineering, July 2005. Thesis: *Synchronization in modular complex networks.*

6. Satish Krishamoorthy, Electrical Engineering, November 2005. Thesis: *Stochastic resonance and noise-induced synchronization in electronic circuits.*

7. Lakshmi Rajagopalan, Electrical Engineering, May 2006 (expected). Thesis: *Noise-induced intermittency in spatially extended dynamical systems described by partial differential equations.*

5 List of Publications

1. A. E. Motter, Y.-C. Lai, and C. Grebogi, "Reactive dynamics of inertial particles in nonhyperbolic chaotic flows," *Physical Review E* **68**, 056307(1-5) (2003).

2. Y. Do and Y.-C. Lai, "Superpersistent chaotic transients in physical space - advective dynamics of inertial particles in open chaotic flows under noise," *Physical Review Letters* **91**, 224101(1-4) (2003).

3. Y.-C. Lai, Z. Liu, and N. Ye, "Infection propagation on growing networks," *International Journal of Modern Physics B* **17**, 4045-4061 (2003).

4. Y. Do and Y.-C. Lai, "Statistics of shadowing time in nonhyperbolic chaotic systems with unstable dimension variability," *Physical Review E* **69**, 016213(1-10) (2004).

5. X.-G. Wang, M. Zhan, C.-H. Lai, and Y.-C. Lai, "Strange nonchaotic attractors in random dynamical systems," *Physical Review Letters* **92**, 074102(1-4) (2004).

6. T. Nishikawa, Y.-C. Lai, and F. C. Hoppensteadt, "Capacity of oscillatory associative-memory networks with error-free retrieval," *Physical Review Letters* **92**, 108101(1-4) (2004).
   This work was featured in *Physical Review Focus* (Week of March 12, 2004):
   http://focus.aps.org/story/v13/st12

7. Y.-C. Lai and Z. Liu, "Effect of noise on the neutral direction of chaotic attractor," *Chaos* **14**, 189-192 (2004).

8. L. Zhao, Y.-C. Lai, R. Wang, and J.-Y. Gao, "Limits to chaotic phase synchronization," *Europhysics Letters* **66**, 324-330 (2004).

9. K. Park, Y.-C. Lai, Z. Liu, and A. Nachman, "Aperiodic stochastic resonance and phase synchronization," *Physics Letters A* **326**, 391-396 (2004).

10. I. B. Schwartz, D. S. Morgan, L. Billings, and Y.-C. Lai, "Multi-scale continuum mechanics: From global bifurcations to noise-induced high-dimensional chaos," *Chaos* **14**, 373-386 (2004).

11. Z. Liu, Y.-C. Lai, and A. Nachman, "Enhancement of detectability of noisy signals by stochastic resonance in arrays," *International Journal of Bifurcation and Chaos* **14**, 1655-1670 (2004).

12. T. Nishikawa, F. C. Hoppensteadt, and Y.-C. Lai, "Oscillatory associative memory network with perfect retrieval," *Physica D* **197**, 134-148 (2004).

13. Y. Do and Y.-C. Lai, "Extraordinarily superpersistent chaotic transients," *Europhysics Letters* **67**, 914-920 (2004).

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26. J. Seoane, J. Aguirre, M. A. F. Sanjuan, and Y.-C. Lai, "Dissipative chaotic scattering and basin topology in continuous-time Hamiltonian systems," *Chaos*, accepted.

27. S.-G. Guan, Y.-C. Lai, and C. H. Lai, "Effect of noise on generalized chaotic synchronization," *Physical Review E*, accepted.

28. Y.-C. Lai and K. Park, "Noise sensitive measure for characterization of stochastic resonance in biological oscillators," *Mathematical Biosciences and Engineering*, accepted.

29. A. Kandangath, S. Krishnamoorthy, Y.-C. Lai, and J. A. Gaudet, "Inducing chaos in electronic circuits by resonant perturbations," submitted to *IEEE Transactions on Circuits and Systems I*.

30. K. Park, S. Krishnamoorthy, Y.-C. Lai, and A. Kandangath, "Noise-induced phase synchronization: nonmonotonicity and stochastic resonance," submitted to *Chaos.*

31. X.-G. Wang, Y.-C. Lai, and C. H. Lai, "Characterization of noise-induced strange nonchaotic attractors," submitted to *Physical Review E.*

32. K. Park, L. Huang, and Y.-C. Lai, "Desynchronization waves in complex networks," submitted to *Physical Review Letters.*

33. Y.-C. Lai, "Extreme fluctuations of finite-time Lyapunov exponents in chaotic systems," submitted to *Chaos.*

34. X.-G. Wang, Y.-C. Lai, and C. H. Lai, "Effect of resonant frequency mismatch on attractors," submitted to *Chaos.*

35. L. Rajagopalan, Y.-C. Lai, K. Park, and G. Hu, "Noise-induced intermittent energy bursts in nonlinear waves," submitted to *Physical Review Letters.*

36. K. Park, Y.-C. Lai, and S. Krishnamoorthy, "Noise sensitivity of phase-synchronization time in stochastic resonance: theory and experiment," submitted to *Physical Review E.*

6 Interactions/Transitions

The PI has been collaborating with Dr. John Gaudet and Dr. Michael Harrison from AFRL at the Kirtland Air Force Base.

During the three-year project period, the PI delivered over 30 invited lectures, seminars, and colloquia at various conferences and universities.

1. "Structure and dynamics of complex networks," Invited plenary talk, *Networks - Structure, Dynamics, and Function*, Los Alamos National Laboratory Center for Nonlinear Studies 23rd Annual Conference, Santa Fe, May 12, 2003.

2. SIAM Conference on Dynamical Systems, Snowbird, Utah, May 26-31, 2003, two invited minisymposium talks: (1) "Coherence resonance in chaotic systems," and (2) "Shadowing of statistical averages in chaotic systems."

3. "Complex networks and security issues," Lockheed Martin/ASU Joint Seminar on Opportunities in Industry, ASU, September 16, 2003.

4. "Synchronization in complex networks," Invited plenary talk, International Workshop on Dynamical Systems and Appliations to Biology, National Center for Theoretical Sciences, Hsin Chu, Taiwan, November 25, 2003.

5. "Transition to chaos in random dynamical systems," Invited plenary talk, Dynamics Days 2004 (23rd Annual International Conference on Nonlinear Dynamics and Complex Systems), Chapel Hill, North Carolina, January 2, 2004.

6. "Transition to chaos in random dynamical systems," Invited talk, AMS Joint Meeting, Phoenix, Arizona, January 9, 2004.

7. "Transition to chaos in random dynamical systems," Colloquium, Department of Applied Analysis and Complex Dynamical Systems, Kyoto University, Kyoto, Japan, March 15, 2004.

8. "Synchronization in complex networks," Seminar, Department of Applied Analysis and Complex Dynamical Systems, Kyoto University, Kyoto, Japan, March 16, 2004.

9. "Synchronization in complex networks," Contributed talk, Fifth International Conference on Complex Systems, Boston, May 18, 2004.

10. "Strange nonchaotic attractors," Invited talk, Third Asian-Pacific Dynamics Days Conference, National University of Singapore, Singapore, July 2, 2004.

11. "Synchronization in complex networks," Joint Colloquium, Department of Mathematical Science and Department of Electrical Engineering, New Mexico State University, August 30, 2004.

12. "Characterization of stochastic resonance," Invited plenary talk, International Workshop on Stochastic Resonance: New Horizons in Physics and Engineering, Max-Planck Institute for Physics of Complex Systems, Dresden, Germany, October 5, 2004.

13. "Characterization of stochastic resonance by phase synchronization," Joint Colloquium, Centre for Nonlinear and Complex Systems and Department of Physics, Hong Kong Baptist University, Hong Kong, China, March 15, 2005.

14. "Synchronization in complex networks," Joint Colloquium, Centre for Chaos Control and Synchronization and Department of Electronic Engineering, City University of Hong Kong, Hong Kong, China, March 18, 2005.

15. "Inducing chaos and stochastic resonance in electronic circuits," Invited talk, MURI meeting on Chaos and Disruption of Circuits, University of Maryland, College Park, May 13, 2005.

16. "Noise-induced superpersistent chaotic transients," Invited minisymposium talk, SIAM Conference on Applications of Dynamical Systems, Snowbird, Utah, May 25, 2005.

17. "Synchronization in complex networks," Seminar, Brazilian Institute for Space Research (INPE), São José dos Campos, Brazil, June 3, 2005.

18. "Inducing chaos by resonant perturbations: theory and experiment," Seminar for Graduate Program on Applied Computing, Brazilian Institute for Space Research (INPE), São José dos Campos, Brazil, June 3, 2005.

19. "Phase synchronization and applications to stochastic resonance and nonstationary signal analysis," Invited plenary Talk, 4th DINCON - Congress on Dynamics, Control, and Applications, UNESP, Bauru, Brazil, June 7, 2005.

20. "Attack-induced cascades in complex networks: mechanism and prevention," Seminar, Department of Computer Science, University of São Paulo at São Carlos, Brazil, June 8, 2005.

21. "Noise-induced superpersistent chaotic transients," Colloquium, Institute of Physics, University of São Paulo, São Paulo, Brazil, June 9, 2005.

22. "Inducing chaos by resonant perturbations: theory and experiments," Nonlinear Dynamics Seminar, Institute of Physics, University of São Paulo, São Paulo, Brazil, June 10, 2005.

23. "Noise promotes species diversity in nature," Invited lecture, International School of Solid State Physics, 35th Course: 100 Years of Brownian Motion, Erice-Sicily, Italy, July 31, 2005.

24. "Attack-induced cascades in complex networks: mechanism and prevention," Seminar, Department of Medicine, UCLA, August 4, 2005.

25. “Dynamics on complex networks: synchronization and cascades,” Short Course (3 hours), Second Forum on Complex Networks, China Center for Advanced Science and Technology, Beijing, China, October 16, 2005.

26. “Attack-induced cascading breakdown of complex networks: mechanism and prevention,” Invited plenary Talk, Second Forum on Complex Networks, China Center for Advanced Science and Technology, Beijing, China, October 17, 2005.

27. “Attack-induced cascading breakdown of complex networks: mechanism and prevention,” Seminar, Institute of Mathematics and Systems Science, Chinese Academy of Sciences, Beijing, China, October 17, 2005.

28. “Noise-induced superpersistent chaotic transients,” Colloquium, Department of Physics, Beijing Normal University, Beijing, China, October 18, 2005.

29. “Attack-induced cascading breakdown of complex networks: mechanism and prevention,” Seminar, Department of Physics, Seoul National University, Seoul, Korea, December 14, 2005.

30. “Inducing chaos by resonant perturbations: theory and experiments,” Seminar, Department of Physics, National University of Singapore, Singapore, February 8, 2006.

31. “Attack-induced cascading breakdown of complex networks,” Invited plenary talk, International Symposium on *Topological Aspects of Critical Systems and Networks*, Hokkaido University, Sapporo, Japan, February 13, 2006.

32. “Synchronization and information propagation on complex modular networks,” seminar, Department of Matheamtics, National University of Singapore, Singapore, March 14, 2006.

7 Past Honors

1. PECASE, 1997.

2. Election as a Fellow of the American Physical Society, 1999. Citation: *For his many contributions to the fundamentals of nonlinear dynamics and chaos.*